...ectional flextensional transducer

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(Received 14 August 1996; accepted for publication 20 February 1997)

A unique low-frequency (900 Hz) class IV flextensional transducer that produces an enhanced far-field pressure on one side and canceled far-field pressure on the other side has been developed. The transducer radiating surface consists of a thick-walled elliptical aluminum shell and a U.S. Navy type III piezoelectric stack along its major axis with two active sections and one inactive section. The directionality is achieved by simultaneously exciting the shell into an omnidirectional and dipole operation by driving stack into both extensional and bending modes. Both measurements and modeling on this device show a front to back pressure ratio of more than 30 dB, producing cardioid-type radiation patterns over an octave band, for a single transducer element. The transducers measured mechanical Q is 8, coupling coefficient is 0.25, and electroacoustic efficiency is 80% and produced a source level of 215 dB *re:* 1 μPa at 1 m when driven at a field limit of 394 kV/m (10 kV/in.) at resonance. The uniqueness of this transducer is its directional beam patterns (directivity index=3.4 dB) and high acoustic output power from a small (less than a third of a wavelength) single element. Six of these transducers were placed in a closely packed line array two-wavelengths long. The array successfully produced narrow directional sound beams (directivity index=8.7 dB) with a front to back ratio greater than 30 dB and a source level of 225 dB *re:* 1 μPa at 1 m. © *1997 Acoustical Society of America.* [S0001-4966(97)03806-X]

PACS numbers: 43.38.Fx, 43.30.Yj, 43.30.Yj [SLE]

INTRODUCTION

Flextensional transducers are used for low-frequency, high-power sound sources in underwater applications. Standard class IV flextensional transducers[1] contain an elliptical shell of inert material such as aluminum or fiberglass, with a drive motor stack of piezoelectric ceramics mounted along the major axis. When the motor is driven the displacement of the sides of the shell are typically much larger than the displacement of the ceramic stack itself, thus producing the large amplitudes necessary for high-power, low-frequency, underwater sound generation.

Since flextensional transducers are small compared to the wavelength of sound at resonance, and because the majority of the surface area of the shell moves in phase, the acoustic radiating patterns from the transducers are nearly omnidirectional. This creates a significant problem in designing arrays that are to radiate in only one direction. At the present time, such arrays must be fabricated utilizing large baffles or rows of transducers spaced and phased to give directional patterns. This requirement for massive, expensive baffles or multiple lines can be eliminated by using a flextensional transducer which radiates in only one direction.

This development is an extension of the previous work on a 3.25-kHz directional flextensional transducer.[2] The original directional flextensional transducer was designed so that the frequencies of both the omnidirectional mode of vibration, which is also called the quadrupole mode, and the bending mode of vibration exist close to each other. (Here the quadrupole mode refers to the four nodes of a class IV flextensional transducer shell, rather than the radiation beam pattern type. The quadrupole mode produces a nearly omnidirectional radiation beam pattern since the majority of the surface area of the shell moves in phase and also these transducers are generally smaller than a half wavelength.) During operation, both of these modes were excited simultaneously, resulting in one side of the shell remaining relatively stationary, while the other side moves in and out, thus producing a flextensional transducer operating in a directional mode.[3]

During this development, the method of driving the transducer was improved thereby allowing higher sound power levels and an optimized front to back ratio. Lower-frequency 900-Hz transducers were fabricated,[4] tested, and installed into a six-element line array. Both measurements and modeling on this device show a front to back pressure ratio of more than 30 dB, producing cardioid type radiation patterns for a single element and narrow-beam radiation patterns for the six-element line array (see Fig. 1) of over an octave frequency bandwidth.

[a]Portions of this paper were presented at the 3rd Joint (132nd) Meeting of the Acoustical Societies of America and Japan, Honolulu, HI [J. Acoust. Soc. Am. 100, 2730(A) (1996)].

A low-frequency direct[illegible] and line array[a]

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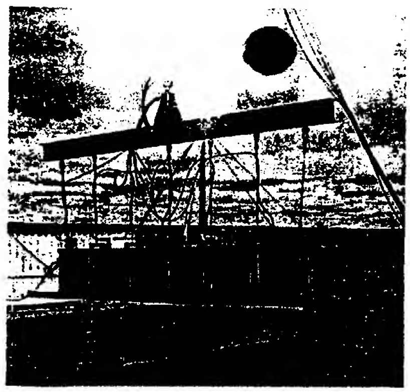


FIG. 1. Photograph of the 900-Hz directional flextensional six-element two-wavelength long line array prior to testing, showing side A.

I. THEORY OF OPERATION AND MODELING

We present here the theory of operation of two methods of drive which can be used to achieve directionality in class IV flextensional transducers under either array or single-element applications, respectively.[4] We first review the condition for displacement drive directionality and then introduce the condition for pressure field directionality.

The directional flextensional transducer achieves directionality by simultaneously combining the shell quadrupole mode with a shell/stack dipole mode. In one means of excitation the two modes are driven together to create a displacement reduction on one surface and enhancement on the opposite surface. This case allows potentially unidirectional operation from planar arrays and modest directional operation for a single element. In the second means of excitation the two modes are driven to create a pressure reduction in one direction and a pressure enhancement in the other direction. This second case allows unidirectional operation from a single element or a line array of elements.

The unidirectional mode is achieved by simultaneously exciting the flextensional transducer into its fundamental quadrupole mode (which is essentially omnidirectional) and also into its fundamental dipole mode. The excitation of the dipole mode is accomplished by driving the piezoelectric stack into a bending mode which causes the shell to move in an oscillatory way as a reaction to the stack bending motion. The stack bending mode is excited by dividing the stack into two separate electrical parts and driving them out of phase to cause bending. The conventional omnidirectional quadrupole mode is excited by driving the two sides of the stack in phase. The combined directional results are canceled motion on one side and enhanced motion on the other side.[3]

The drive scheme is illustrated in Fig. 2 showing two halves of a drive stack assembly. To excite the quadrupole mode we put equal polarity values $+E_q$ on side A and $+E_q$ on side B of the stack. To excite the dipole mode we put opposite polarity values such as $+E_d$ on the left and $-E_d$ on the right side. We sum both of these modes to obtain the directional mode. In this case with E_A the total voltage on side A and E_B the total voltage on side B we would have

$$E_A = E_q + E_d \quad \text{and} \quad E_B = E_q - E_d. \tag{1}$$

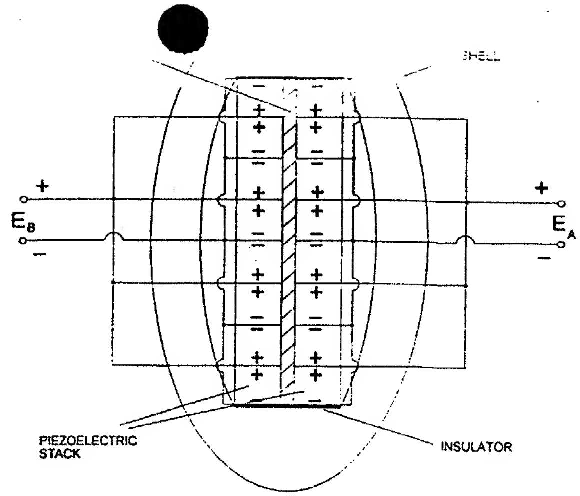


FIG. 2. Example of an electrical drive arrangement for the simultaneous excitation of the quadrupole and dipole modes leading to the creation of the directional mode.

For the simple case where E_d is set equal to E_q we have $E_A = 2E_q$ and $E_B = 0$. In this case only one half of the ceramic stack would be driven. This assumes that equal drives yield equal displacement amplitudes. If the displacement of the dipole mode were twice as much at resonance due to a higher mechanical Q, the dipole drive voltage should be reduced to $E_d = E_q/2$ yielding the drive condition $E_A = (3/2)E_q$ and $E_B = E_q/2$ or the ratio condition $E_A/E_B = 3$.

For the most effective operation the directional flextensional transducer is designed so that the transducer dipole mode resonates in the vicinity of the transducer quadrupole mode resonances. Since the dipole and quadrupole amplitudes and phase may not be the same at the desired operating frequency, the dipole mode may require a different amplitude and phase drive condition to attain reduced motion on one surface. Moreover, if the desire is to attain a deep pressure null on one side an additional 90° phase shift may be required to compensate for the quadrature related radiation characteristics of the dipole and monopole sources.

If planar array operation is desired, then the cancellation of the displacement on one surface (say the back surface) should be the goal. However, for a single element or line array stationary motion on one surface may not be sufficient for directionality since the front surface radiation may be diffracted around to the back as a result of the small size of the element. In this case the goal should be the cancellation of the pressure in the back direction.

The cancellation of the pressure in one direction can be understood by considering the case of an ideal spherical radiator, of radius a, operating in both an omnidirectional (pulsating) and a dipole (oscillating) mode of vibration. First let p_o and v_o be the pressure and velocity in the omnidirectional mode and p_d and v_d be the pressure and velocity in the dipole mode. Then with k the wave number, $2\pi/\lambda$, it can be shown that the dipole pressure can be written in terms of the omnidirectional pressure as

$$p_d = p_o \cos(\theta)(v_d/v_o) jka/(1 + jka), \tag{2}$$

...om the direction of the maximum ...ode and ...$\sqrt{(-1)}$. With the sphere ... modes with co...ponding modal velocities v_o and v_d the total pressure $p_t=p_o+p_d$ is then

$$p_t=p_o[1+\cos(\theta)(v_d/v_o)jka/(1+jka)]. \quad (3)$$

In the high-frequency range we get the approximation

$$p_t \cong p_o[1+\cos(\theta)(v_d/v_o)], \quad ka \gg 1 \quad (4)$$

while in the low-frequency range we get

$$p_t \cong p_o[1+jka\cos(\theta)(v_d/v_o)], \quad ka \ll 1. \quad (5)$$

The intermediate frequency range is generally located just above the quadrupole resonance for a class IV transducer.

We see that in the high-frequency range we get a cardioid type $[1+\cos(\theta)]$ condition for velocity cancellation on one side. This condition should also apply to the case of an array that is large compared to wavelength of sound. In the lower frequency range it can be seen that there must also be a 90° phase shift and frequency dependence between the velocities in order to arrive at $jka(v_d/v_o)=1$ and achieve the cardioid pressure function $[1+\cos(\theta)]$. That is, for a cardioid function we would need to electrically drive the dipole mode so that the dipole velocity $v_d=v_o/jka$.

The cardioid function may be obtained over a broad frequency range if the dipole velocity follows the relation

$$v_d=v_o(1+1/jka), \quad (6)$$

as may be seen from Eq. (3). The 90° phase difference at low frequency and the zero phase difference at high frequencies between the two modes can be generalized and applied to most transducers including the class IV flextensional. The combined use of monopole and dipole operation of a spherical transducer has been described by Ehrlich.[5]

At high frequencies we would not expect to need a phase shift between the quadrupole and dipole modes while at low frequencies an additional 90° phase shift on the dipole mode would be needed to accomplish the desired results. If in addition to this, the dipole mode operates with twice the output at resonance (e.g., due to a higher mechanical Q as a result of the lower radiation loading) the drive condition for pressure cancellation would be $E_d=jE_q/2$ yielding $E_A=E_q(1+j/2)$ and $E_B=E_q(1-j/2)$ or $E_A/E_B=3/5+j4/5$ yielding an amplitude ratio of unity and phase angle difference between stack sides A and B given by 53°. The corresponding condition for displacement cancellation was shown earlier to be a less favorable amplitude ratio of three with no phase difference between the two sides.

The transducer was modeled using the ANSYS[6] finite element program which contains structural, piezoelectric, and acoustical fluid elements. Our ANSYS results were limited to a 2-D model which under fluid loading conditions corresponds to the results for a long line array rather than a short single element.

In Fig. 3 we show computed ANSYS results for both displacement and pressure cancellation for the 900-Hz design. The top figure is for the case of displacement cancellation showing a smaller front to back ratio below resonance due to back diffraction. However, because of self-baffling, there is an improved ratio above r... the ...rupole is driven ...e volt and th... is driven ... one-half volt to compensate for th... this mode. One part of the stack is driven at 1.5 V and ... other part is driven at 0.5 V. The lower illustration is for the same mechanical Q conditions but with the dipole additionally phase shifted by 90°. This yields identical stack sectional voltage magnitudes and a phase shift of 53° as discussed earlier. This condition yields greater output and an improved front to back ratio below resonance. A reduction in phase difference above resonance yields improved front to back ratios above resonance.

The ANSYS theoretical predictions for velocity or pressure cancellation were based on a given drive condition between the quadrupole and dipole modes. One would expect that an optimized frequency-dependent amplitude and phase drive condition could yield a large front to back ratio over a broad range of frequencies. From the above discussion of the ideal spherical radiator we would expect that the required wideband dipole velocity response should follow Eq. (6), with v_o replaced by v_q yielding

$$v_d \cong v_q(1+1/jka). \quad (7)$$

However, because the two modes may have different resonant frequencies and a class IV flextensional is not an ideal sphere, this relation between v_d and v_o is an over simplification.

In practice we usually have direct control of the input voltages rather than the modal velocities. Accordingly, an accurate model of the transducer in both the nearly omnidirectional quadrupole and dipole modes is needed. Although ANSYS yields reasonably good predictions, it is not accurate enough to predict deep nulls in the back radiation where a near exact prediction of the separate omnidirectional and dipole pressure amplitudes and phases are needed. Another approach is to separately measure the on-axis omnidirectional (quadrupole) and dipole amplitude and phase responses of the transducer or array of transducers for a given voltage input. From this information the dipole input voltage amplitude may be adjusted so that the on-axis pressure amplitudes and phases match that of the quadrupole mode. Since the dipole mode has two lobes of opposite phase, one lobe will add to the quadrupole (omnidirectional) mode and the other will cancel yielding a null on one side and a pressure increase on the other side.

This method may be described mathematically through Eq. (1) written as

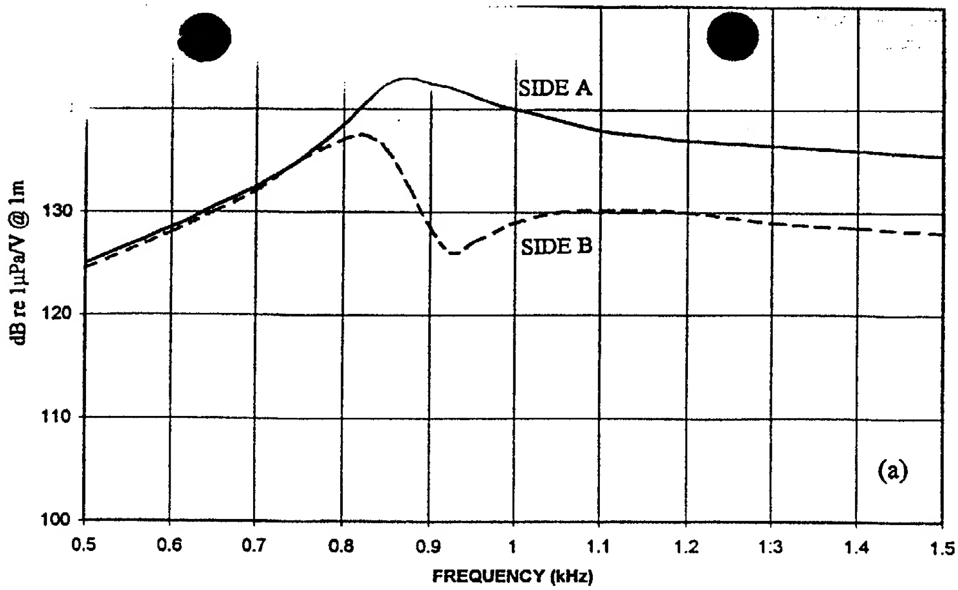
$$E_B/E_A=(1-R)/(1+R), \quad \text{where} \quad R=E_d/E_q. \quad (8)$$

Thus given the desired complex ratio R of dipole and quadrupole drives we can determine the corresponding complex voltage ratio for sides A and B of the piezoelectric stack.

In order to relate this to the pressure response levels let the transmitting voltage response (TVR) for the dipole p_d and quadrupole p_q mode pressures be

$$\text{TVR}_d=p_d/E_d \quad \text{and} \quad \text{TVR}_q=p_q/E_q. \quad (9)$$

For a null in one direction the pressures should be equal; i.e., $p_d=p_q$, leading to the required condition $E_d=p_q/\text{TVR}_d$ so



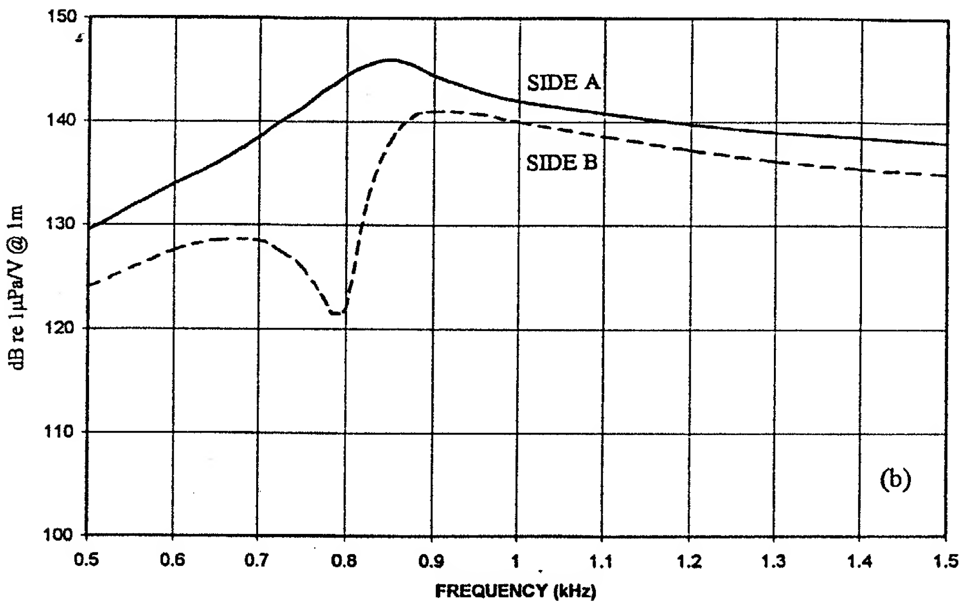


FIG. 3. ANSYS finite-element modeled transmitting voltage response operating in the directional (a) displacement mode, $E_A=1.5$ and $E_B=0.5$ ($E_q=1$, $E_d=0.5$) and (b) pressure mode, $E_A=1$ and $E_B=1$ at 53° ($E_q=1$, $E_d=0.5$ at 90°).

that for this case R, which is equal to E_d/E_q, is given by

$$R=\mathrm{TVR}_q/\mathrm{TVR}_d. \tag{10}$$

Thus, the complex quantity R is determined by the complex ratio of the quadrupole and dipole constant voltage transmitting responses yielding the desired complex ratio of the voltages on each side of the stack through the equation

$$E_B/E_A=(1-R)/(1+R). \tag{11}$$

This expression, which is written in complex quantities, may also be written in terms of amplitude and phase quantities for ease in measured data reduction and voltage drive application.

II. THE PHYSICAL MODEL AND MEASURED RESULTS

The transducer is composed of two elliptical aluminum shells each 7.5-in. (19.05-cm) high, a wall thickness of 1.2 in. (3.05 cm), and semimajor and semiminor axes radii of 8.1 in. (20.57 cm) and 3.1 in. (7.87 cm), respectively. A piezoelectric ceramic stack is inserted along the major axis of the shell. Each ceramic stack is 13-in. (33.02-cm) long, 6-in. (15.24-cm) high, 3-in. (7.62-cm) thick, and composed of 52 U.S. Navy type III 1/4-in. (6.35-mm) thick ceramic plates stacked in series. The ceramic plates were manufactured with an inactive central margin, by removing 1/4 in. (6.35-mm) of silver electrodes from the surface on both the top and bottom of the plates. All of the electrodes on each side of the stack

TABLE I. Measured transmit response of omnidirectional and dipole mod[illegible] the [illegible] [illegible]dition for a directional mode at 900 Hz.

	TVR_q		TVR_d		R		[illegible]	[illegible])	Measured
	Level	Phase	Level	Phase	Level	Phase	Magnitu[illegible]	[illegible]hase	Front/Back
Single element	141.4 dB	70.6°	151.2 dB	−67.8°	−9.8 dB	238.4°	0.728	−31.6°	55 dB
Array	154.4 dB	−74.4°	161.9 dB	−123.9°	−7.5 dB	49.5°	1.66	38.0°	62 dB

should be E_A / E_B

are electrically connected in parallel permitting each side of the stack to be independently driven for the excitation of the stack bending modes. The shells were pinned together to form the complete transducer and enclosed with a bonded rubber boot banded to two aluminum end plates separated by four stainless-steel rods, giving the transducer overall dimensions of 19.4-in. (49.3-cm) long, 9.5-in. (24.1-cm) wide, 20.3-in (51.6-cm) high, and an in-air weight of 350 lb (147.4 kg). Six of these transducers were fabricated and separately acoustically tested then assembled into a six-element horizontal line array (see Fig. 1) two-wavelengths long with a 20-in. (50.8-cm) center to center spacing. The testing was conducted in a free-field open-water environment at a depth of 308 feet (94 m) to avoid unwanted reflections and cavitation.

The method in Sec. I which describes a mathematical procedure to determine the electrical drive condition for obtaining a large front to back ratio, was used during the testing of the transducer in order to create directional beams. This method requires the measurement of the complex pressure response (magnitude and phase) of the transducer or array in the omnidirectional and dipole modes [see Eq. (9)]. For a pressure null on one side to exist the omnidirectional and dipole pressures must be equal, leading to Eq. (10). This complex quantity R was calculated for both the single transducer element and the array, so that complex drive ratios of E_B/E_A of Eq. (11) could be determined. Table I lists the results at 900 Hz for both the single element and array. This method was used over a wide frequency band and fine adjustments were made with hydrophones placed on opposite sides A and B to obtain the largest front to back ratio as possible.

Each element was tested in the omnidirectional, dipole, and directional mode. In the single element omnidirectional mode, the transducer elements produced a sound-pressure level (SPL) of 211 dB *re:* 1 μPa at 1 m referenced to the flat side of the transducer. The directional mode yielded an increased SPL of approximately 215 dB *re:* 1 μPa at 1 m when driven at the full power field limit of 394 kV/m (10 kV/in). The power based electroacoustic efficiency, measured during the tests, was approximately 80% in both modes. The measured directivity index (DI) of the directional mode at 900 Hz is 3.4 dB and −1.8 dB for omnidirectional mode when referenced to the sides of the shell. The omnidirectional mode mechanical Q is 4 (typical for flextensional transducers), the mechanical Q in the dipole mode is 13 and in the directional mode the mechanical Q is 8. Figure 4 shows the measured omnidirectional, dipole, and directional (cardioid) beam patterns. In Fig. 5 we show the single-element transducer measured transmitting voltage response driven in the fundamental omnidirectional mode (both stack sections A and B driven electrically in phase with the same amplitude), the dipole mode (A and B driven electrically 180° out of phase from each other with the same amplitude), and the directional mode of operation with the phase and amplitude adjusted to obtain a maximum front to back ratio over that frequency band. It is interesting to note that the mechanical Q and transmitting voltage response of the directional mode is approximately the average of the omnidirectional and dipole modes.

In the array configuration all of the side A drive leads were connected in parallel and all of side B drive leads were connected in parallel with each side driven by separate waveform generators and power amplifiers. The six-element line array produced a SPL of 225 dB *re:* 1 μPa at 1 m in the directional mode with a measured operating electroacoustic efficiency of over 80% and a mechanical Q of 4. Radiation patterns yielded back reductions of 53 to 75 dB between 600 and 1400 Hz in a single line of six elements. The array maximum response axis is easily changed by reversing the drive signals producing an array capable of projecting in either the forward or backward directions. The radiation pat-

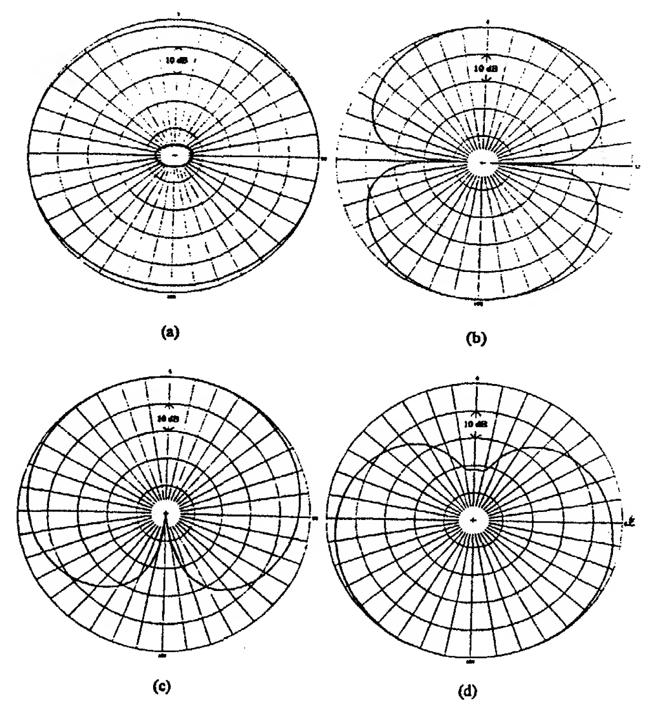


FIG. 4. Measured single-element 900-Hz radiation patterns operating in the (a) quadrupole mode, $E_A = E_B$, (b) dipole mode $E_A = -E_B$, (c) directional mode $E_A/E_B = 0.73$ at 31.6°, and (d) directional mode drive leads reversed.

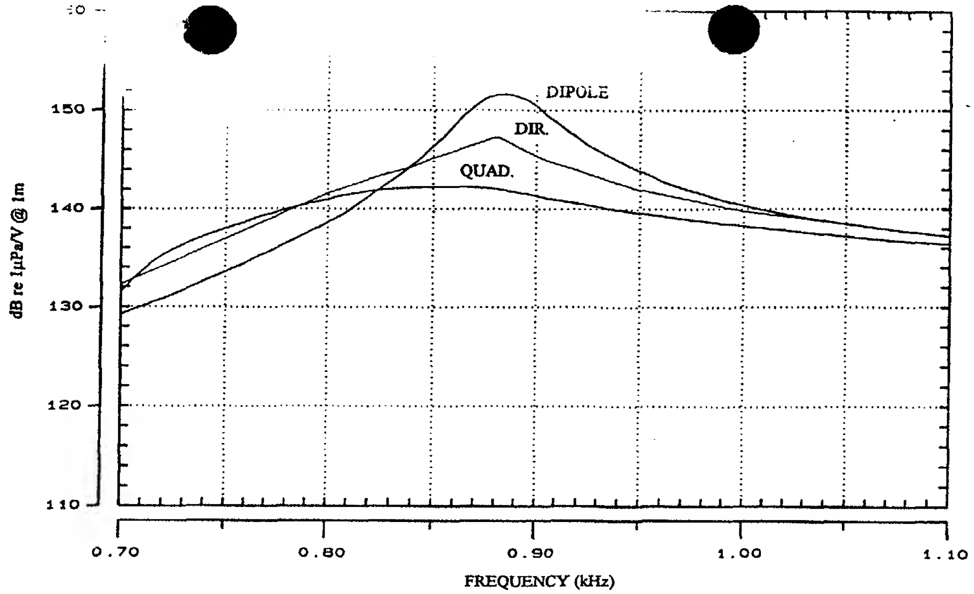
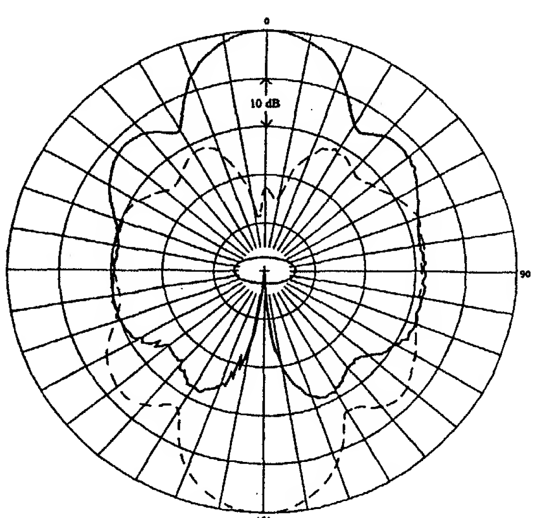


FIG. 5. Measured single-element transmitting voltage response driven in quadrupole, dipole, and directional modes.

ns for the six-element line array are shown in Fig. 6 for array steered in both the forward and backward directions 900 Hz. The measured beamwidth is 27.4° which is close that of an ideal two-wavelength line with a calculated amwidth of 27.8°. Another method of presenting direcnal array performance is through a plot of the TVR across e operating band in the forward and backward direction. In e upper plot of Fig. 7, the top trace is the TVR measured side A of the array, while the lower trace is the B side or ck side TVR. The vertical scale is 20 dB/division to allow e significant front to back ratios to be displayed. The lower ot of Fig. 7 is identical to the upper plot, but the A and B drive leads of the array have been reversed, thereby reversing the direction of radiation.

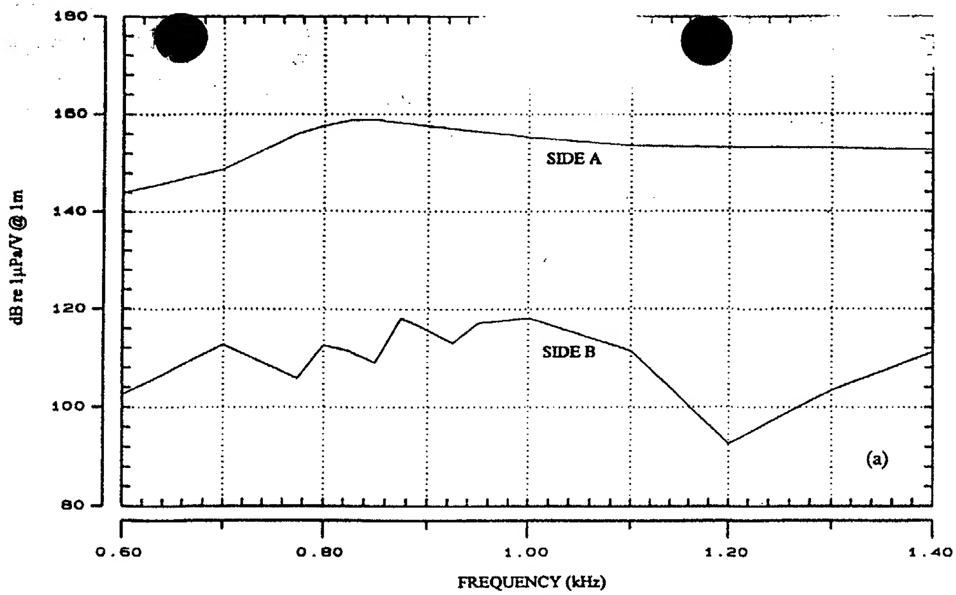


. 6. Measured 900-Hz radiation patterns for the six-element line array rating in the directional mode (—) and with the drive leads reversed ---).

III. SUMMARY AND CONCLUSIONS

We have presented a directional class IV flextensional transducer which can be operated in either displacement or field pressure canceling modes. The transducer uses both the conventional quadrupole mode which is excited by the extensional motion of the piezoelectric stack and a body dipole mode which is excited by the inextensional bending mode of the stack. The piezoelectric stack is separated into two sides so that both sides may be separately energized to excite both modes. The displacement drive condition is the preferred choice for unidirectional planar array applications. The phase shifted pressure drive condition is the choice for single-element or line array applications. This choice yields not only a large front to back ratio but also an increase in source level and greater power capacity since both sides of the stack are simultaneously driven. This method also allows the optimization of the front to back ratio at all frequencies by use of the phase and amplitude transmitting voltage response values of the quadrupole and dipole mode to obtain the required input voltage amplitude and phase for each side of the piezoelectric stack.

The phase shifted pressure drive condition significantly improves operation by providing increased SPL and back reductions of up to 75 dB with both single elements or line arrays. Measured results revealed a directional transducer which operated efficiently in both the normal (omnidirectional) and directional mode. A six-element line array of directional flextensional transducers produced a SPL of over 225 dB *re:* 1 μPa at 1 m with an operating efficiency of over 80%.



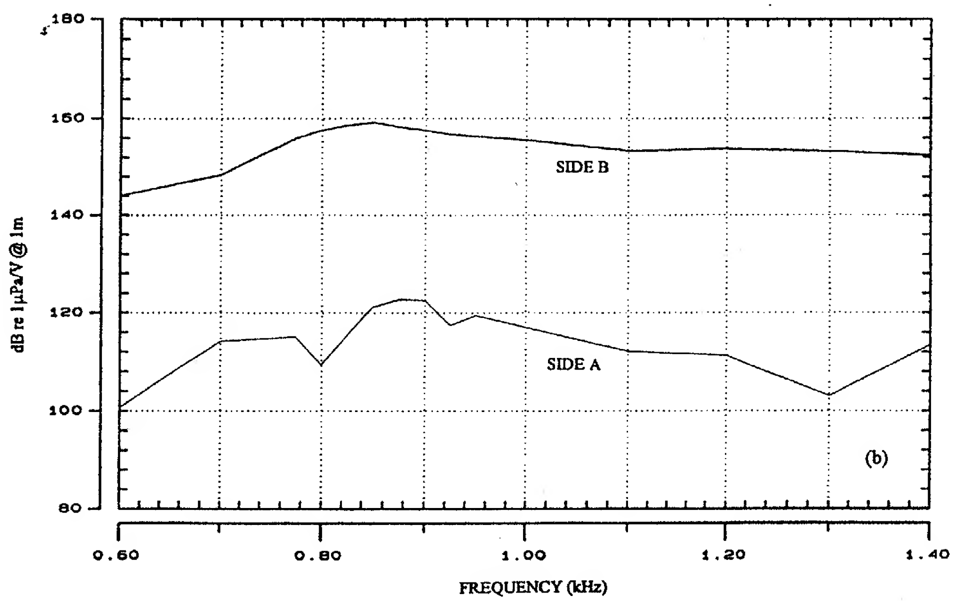


FIG. 7. Measured transmitting voltage responses for the six-element line array operating in the directional mode in the (a) forward (side A) and backward (side B) directions and (b) with the drive leads reversed, forward (side B) and backward (side A).

ACKNOWLEDGMENTS

The authors would like to thank Jan F. Lindberg of the Naval Undersea Warfare Center (NUWC), Newport, RI for his support on this project. Work was performed in a joint venture by Massa Products Corporation and Image Acoustics, Inc., with support, in part through a U. S. Navy SBIR contract.

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